Appendix K

AM Hybrid IBOC DAB Performance Test Report

1. Overview

The USADR AM IBOC DAB system has been carefully designed to provide superior digital audio performance while minimizing the impact to existing analog signals. In the initial phase of development, the system was modeled and simulated to verify that the resulting design would indeed exhibit acceptable performance in an environment comprised of both analog and IBOC signals. As the development progressed, computer models have been replaced by hardware implementations of AM IBOC DAB exciters and receivers. The prototype exciters and receivers are allowing verification of system performance in both a laboratory environment and in the field.

This appendix documents the results of the laboratory performance tests of the USADR AM hybrid IBOC DAB system. These results are important because they verify the performance of a physical implementation of the design under controlled and repeatable conditions.

The quality and coverage of AM broadcasts is often limited by two factors: noise and interference. Interference is caused mainly by other AM stations that either share the same frequency as the desired station (co-channel), or are one or two channels removed (adjacent channel).

In an attempt to faithfully reproduce the full range of expected environments in a controlled laboratory setting, USADR has performed a number of tests to measure the performance of its AM hybrid IBOC DAB system in the presence of various combinations of co- and adjacent channel hybrid IBOC interferers. In particular, the following tests were performed:

Performance in Gaussian Noise: This test measured system performance in the presence of Additive White Gaussian Noise (AWGN).

Performance in the Presence of Interference: This test measured performance in the presence of co-channel and first adjacent hybrid IBOC signals.

Performance in the Presence of Interference and Gaussian Noise: This test measured performance in the simultaneous presence of AWGN and interferers.

2. Definitions and Assumptions

USADR has verified performance of the AM hybrid IBOC system by testing physical implementations of an exciter, channel, and receiver in a laboratory environment. Accurate interpretation of the results is incumbent on a thorough understanding of the assumptions and definitions described below.

2.1. Signal

The AM IBOC hybrid signal consists of an AM carrier modulated by a band limited (± 4.5 kHz) analog signal and digitally modulated subcarriers placed on each side as well as under the main carrier occupying the spectrum within ± 10 kHz. For the following tests, the analog portion of the AM IBOC signal consisted of Pulsed USASI noise. Pulsed USASI noise simulates aggressively processed AM program material. The modulation index was set to 100%.

2.2. Block Error Rate Curves

Performance in a given environment is shown in terms of block error rate curves. Blocks are simply large groups of information bits at the input to the audio decoder. Each block has an assigned Cyclic Redundancy Check ("CRC") that detects errors in a packet of bits. If the CRC is incorrect, the block is deemed in error. Block error rate is computed by dividing the number of blocks in error by the total number of blocks received.

Block error rate is used as a metric since it provides the most accurate indication of the threshold of audibility ("TOA"). TOA is defined as the block error rate above which noticeable audio impairments may just be detected. For the USADR AM hybrid IBOC DAB system, the TOA is defined as 0.01 or 1% block error rate.

C/No, used in the Gaussian Noise test, is defined as the ratio of the power in the AM carrier to the power of the noise in a 1 Hz bandwidth. The noise was produced using a Noise/Com Gaussian noise generator, and was summed with the signal just prior to the receiver input.

2.3. Interference Tests

Interference tests were performed in the presence of various combinations of co-channel and first adjacent channel interferers. USADR's AM hybrid IBOC DAB system has a total bandwidth of 20 kHz and hence the effect of second adjacent interferers is insignificant. Therefore, no testing was performed in the presence of second adjacent interferers. All analog and digital interferers were mutually uncorrelated. The analog portion of the interference signals was modulated with Pulsed USASI noise to improve repeatability and to match the conditions used in the simulations performed in Appendix J.

3. Test Procedures

3.1. Performance in Gaussian Noise

This test measured system performance in the presence of AWGN. Performance is depicted using block error rate curves, which describe the system's block error probability in terms of C/No. The test set-up is shown in Figure K-1. The test procedure is as follows:

1. Transmit a desired hybrid IBOC signal. Add white Gaussian noise at a level that produces the desired C/No.

2. Run until either 100-block errors are observed, or 10 minutes have elapsed, whichever takes longer. Record the block error rate.

3. Repeat Steps 1 and 2 for a least two other points. Attempt to set the C/No so that the resulting curve intersects the TOA.

3.2. Performance in the Presence of Interference

Performance is depicted using block error rate curves, which describe the system's block error probability in terms of the level of the interferers relative to the desired signal. The test set-ups are shown in Figures K-2 through K-4. The test procedure is as follows:

1. Transmit a desired hybrid IBOC signal.

2. Add hybrid IBOC upper and lower first adjacent interferers.

3. Run until either 100-block errors are observed, or 10 minutes have elapsed, whichever takes longer. Record the block error rate.

4. Repeat steps 1 and 2 for at least one other point. Attempt to set the power of the interferer(s) so that the resulting curve intersects the TOA.

5. Remove one of the interferers such that the other interferer's performance can be measured.

6. Repeat steps 1 through 4, replacing the upper first adjacent interferer with a co-channel interferer.

3.3. Performance in the Presence of Interference and Gaussian Noise

This test measured system performance in the presence of a single first adjacent or co-channel hybrid IBOC interferer and AWGN. Performance is depicted using block error rate curves, which describe the system's block error probability in terms of C/No for the AWGN and the level of the interferer relative to the desired signal. The test set-up is shown in Figures K-2 and K3. The test procedure is as follows:

1. Transmit a desired hybrid IBOC signal.

2. Add a hybrid IBOC first adjacent interferer.

3. Run until either 100 block errors are observed or 10 minutes have elapsed, whichever takes longer. Record the block error rate.

4. Repeat steps 1 and 2 for at least one other point. Attempt to set the C/No (by raising/lowering the noise) so that the resulting curve intersects the TOA.

5. Repeat steps 1 through 4, replacing the first adjacent interferer with a single co-channel interferer.

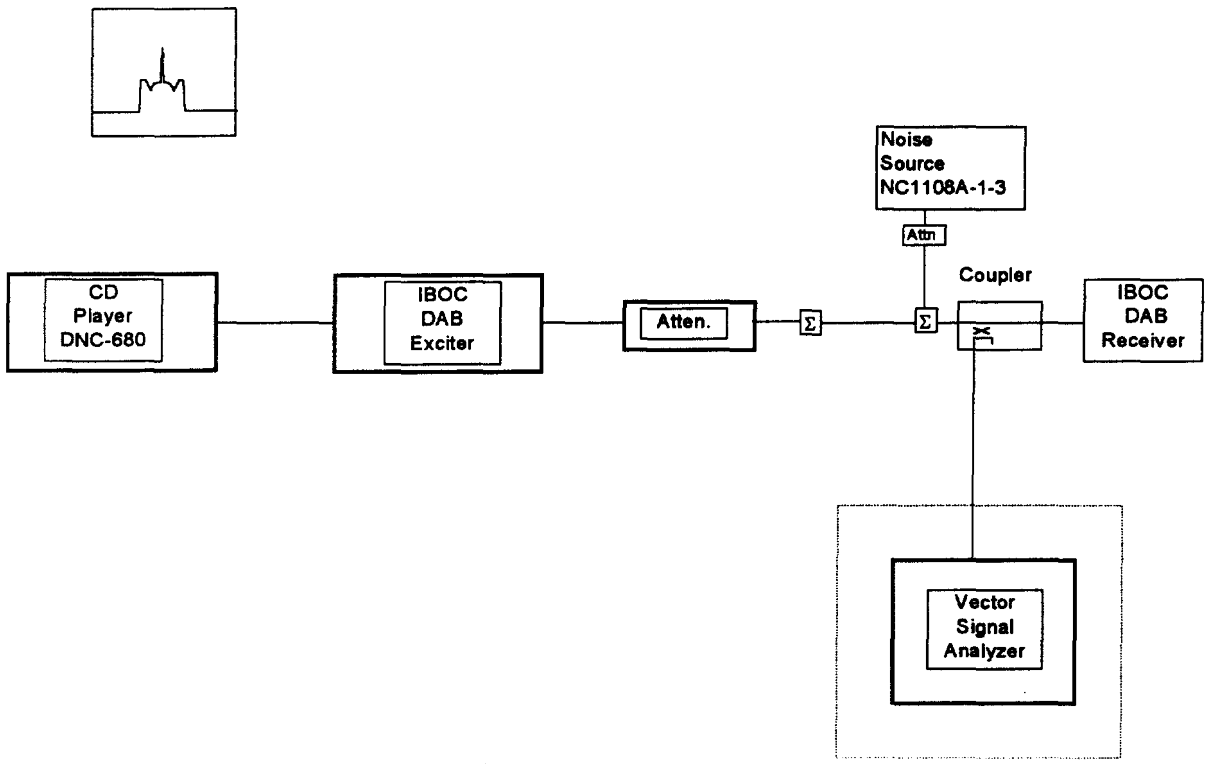


Figure K-1 Test setup for testing with no interferers present.

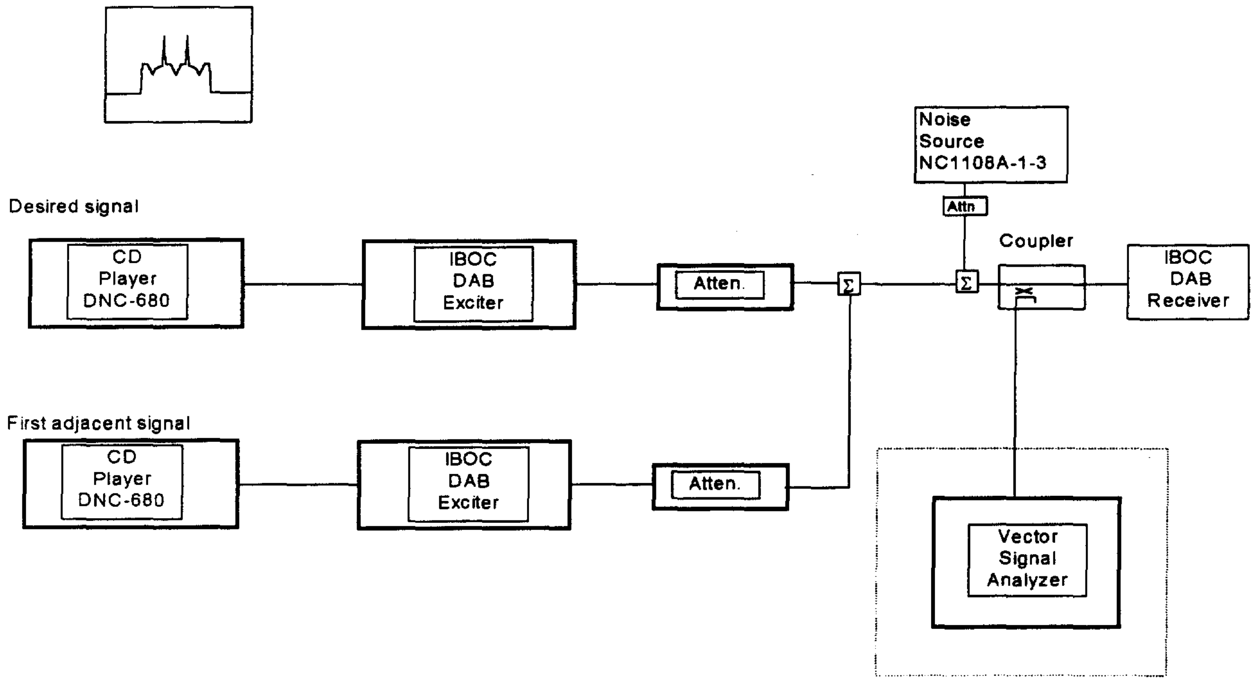


Figure K-2 Test set-up for testing with first adjacent interferers present.

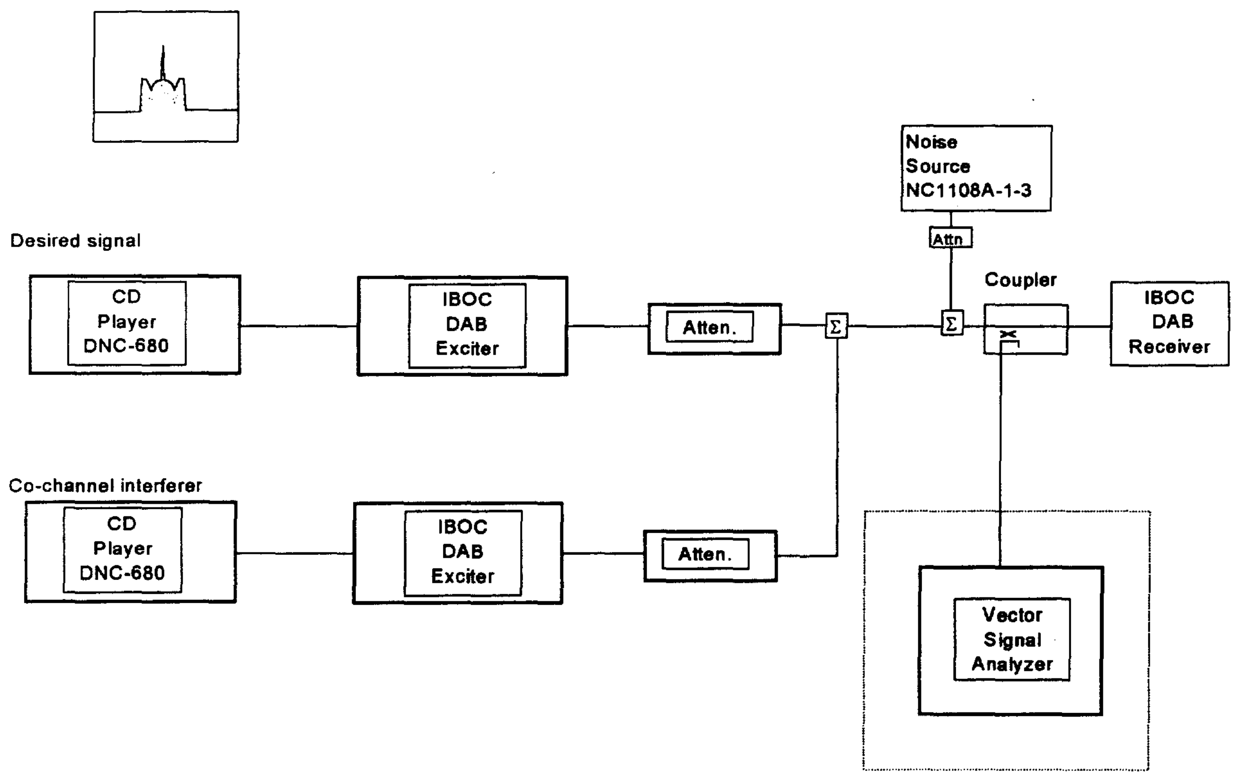
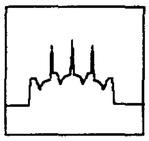


Figure K-3 Test set-up used for co-channel interference tests.



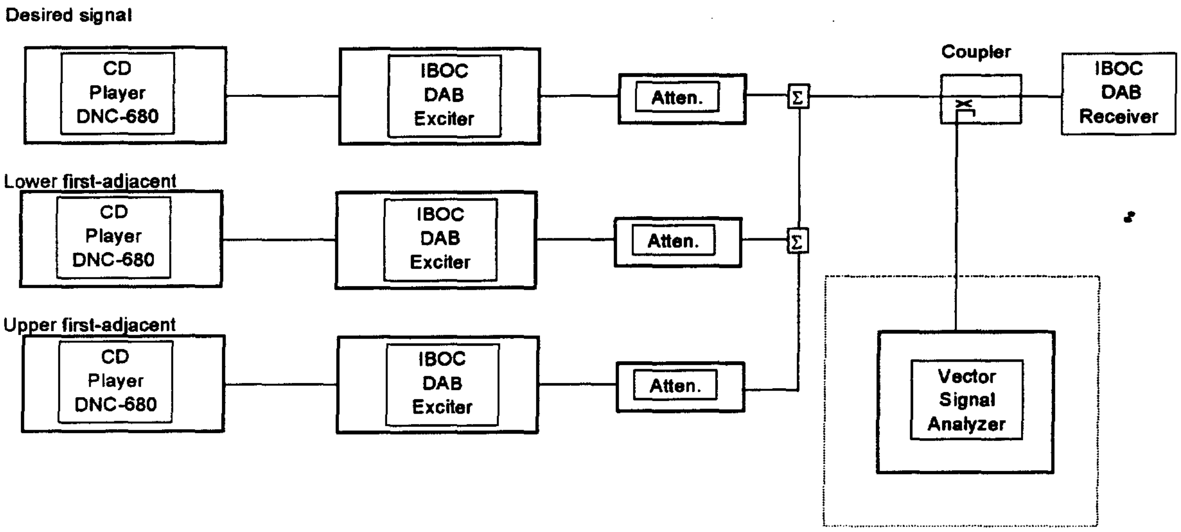


Figure K-4 Test set-up for dual first adjacent testing.

4. Test Results

USADR has performed laboratory performance tests to characterize the performance of the hybrid IBOC digital signal in the presence of Gaussian noise and interference. The results are summarized in Tables K-1 thru K-4. The interference level is given in units of dBc, which is defined as dB relative to the carrier power of the desired hybrid signal.

4.1. Performance in Gaussian Noise

Performance in Gaussian noise is shown in the block error rate curves of Figure K-7, and is summarized in Table K-2 below. Comparing these results with those of Appendix J it can be seen that the hardware and software implementation of the system performs nearly identically to that predicted by the simulations. As can be seen from either Figure K-7 or Table K-1 the TOA is approximately 71.5 dB/Hz.

Table K-1 AM IBOC performance results in the presence of AWGN.

C/No (dB/Hz)	Block Error Rate
72.8	0.010%
71.8	0.077%
70.8	2.024%

4.2. Performance in the Presence of Interference

Results for performance in the presence of interference are shown in Table K-2. The upper portion of the table shows performance in the presence of lower first adjacent and co-channel interferers. Results from this portion of the table are shown in Figure K-5. As can be seen, TOA for a single first adjacent occurs when the interferer is approximately 5.5 dB above the desired signal. TOA for a co-channel interferer occurs when the interferer is approximately 18.5dB below the desired.

The lower portion of the table shows performance in the presence of lower and upper first adjacent interferers. Results from this portion of the table are shown in Figure K-6. Symmetry of results was assumed in this interference scenario. Comparison of the simulation results in Appendix K with the hardware and software implementation results shows nearly exact agreement.

The FCC mandates that all classes of stations receive 6 dB protections at their 0.5 mV/m contour from first adjacent interference. In addition, the FCC defines the coverage of an AM station as the signal level where its co-channel interferers sum to a signal strength that is 26 dB weaker. The dashed lines in both Figures K-5 and K-6 depict these protected regions. In Figure K-5 the AM IBOC DAB hybrid performance is entirely outside the envelope set by the protected contours. In Figure K-6, the DAB coverage includes a large portion of, but not the entire, protected area. However, the dashed lines in Figure K-6 apply to a signal strength of 0.5 mV/m. For higher desired signal strengths, more coverage area would be obtained. The regions not covered by DAB are those where strong dual first adjacents exist. Based on interference studies done in the past, this situation is rare during daytime operations but may occur at night due to skywave propagation effects. In addition, when both first adjacents are strong many analog radios will also suffer dramatic levels of cross talk from adjacent channel interferers. However, USADR's AM hybrid IBOC DAB system will cover the majority of the regions currently covered by today's analog systems.

Table K-2 Performance results for first adjacent and co-channel interferers. TOA is defined as a block error rate of 1%.

Lower first(dB)	Co-Channel (dB)	Upper First (dB)	Block Error Rate
7	-50		6.9%
6	-50		3.7%
5	-50		0.13%
3	-40		0.00%
0	-26		0.23%
1	-25		0.12%
1	-24		1.9%
1	-23		7.5%
-10	-24		0.0%
-10	-21		3.6%
-10	-20		15.15%
-20	-18		13.8%
-50	-19		2.45%
-50	-20		0.39%
-50	-19		0.16%
-20	-18		3.07%
-20	-17		26.4%
7		-50	11.44%
6		-50	4.41%
0		-32	1.25%
0		-33	0.56%
-10		-27	1.21%
-10		-28	0.88%
-18		-18	0.12%
-19		-19	0.02%

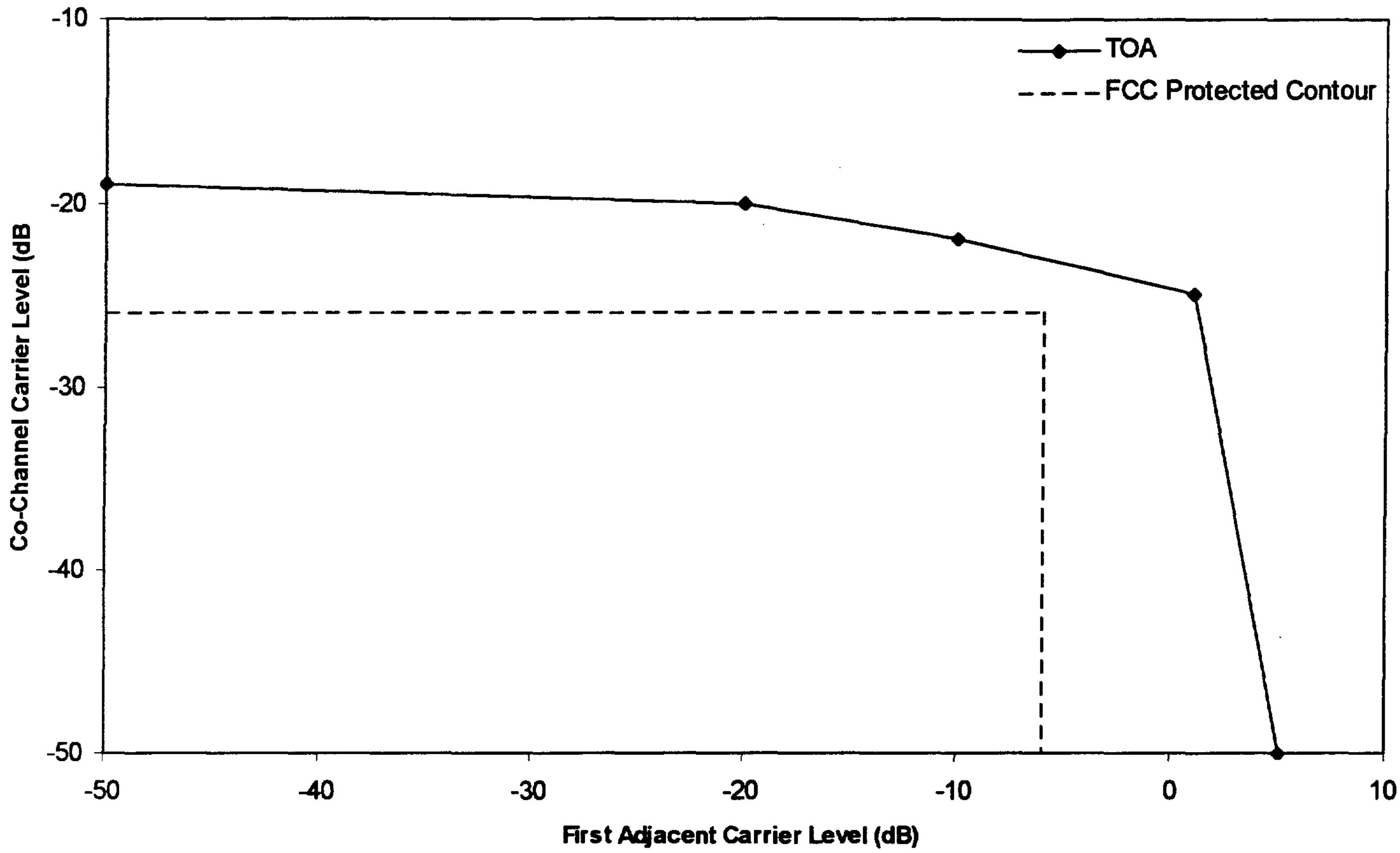


Figure K-5 USADR AM IBOC DAB system performance in the presence of co-channel and first adjacent interferers.

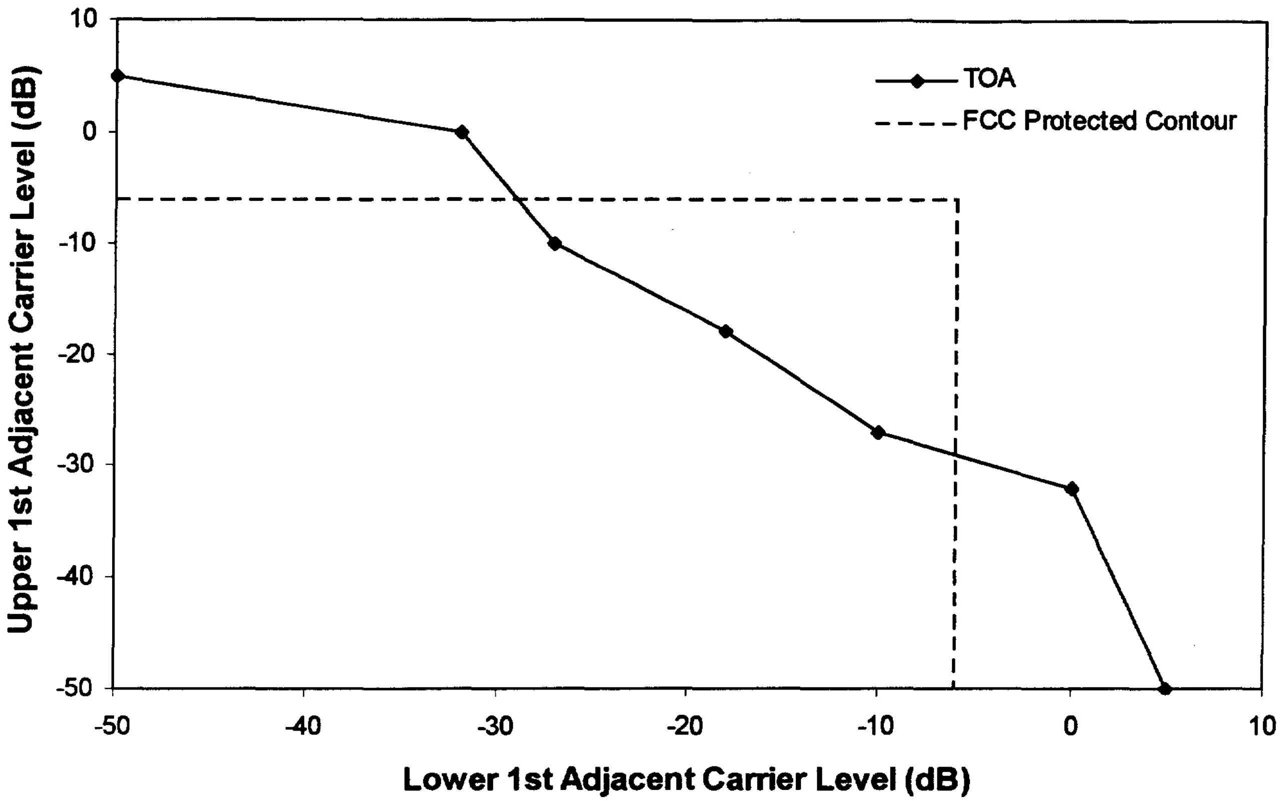


Figure K-6 USADR AM IBOC DAB System performance in the presence of first adjacent interferers.

4.3. Performance in the Presence of Interference and Gaussian Noise

Results showing performance in the presence of AWGN and interferers are given in Figure K-7, and summarized in Table K-3. Figure K-7 shows that the presence of a strong first adjacent interferer has the largest effect on the coverage area of the AM system, as one might expect. On the other hand, co-channel interference below the 26 dB-protected contours has a minimal effect.

Table K-3 Performance in the presence of interference and Gaussian noise. TOA is defined as a block error rate of 1%

Interference Scenarios	C/No (dB/Hz)	Block Error Rate
+6 dB 1st Adjacent Interferer	83.4	0.224%
	82.4	4.036%
	81.4	17.068%
0 dB 1st Adjacent Interferer	79.8	0.796%
	78.6	3.040%
	77.4	8.020%
-6 dB 1st Adjacent Interferer	77.4	0.968%
	76.4	4.00%
	75.4	12.427%
-24 dB 1st Adjacent Interferer	89.4	0%
	86.4	0%
	84.4	0%
-24 dB Co-Channel Interferer	73.4	0.758%
	72.4	4.198%
	71.4	14.938%
-30 dB Co-Channel Interferer	72.4	0.408%
	71.4	2.679%
	70.4	15.395%
-30 dB Co-Channel Interferer	82.4	0%
	81.4	0%
	80.4	0%

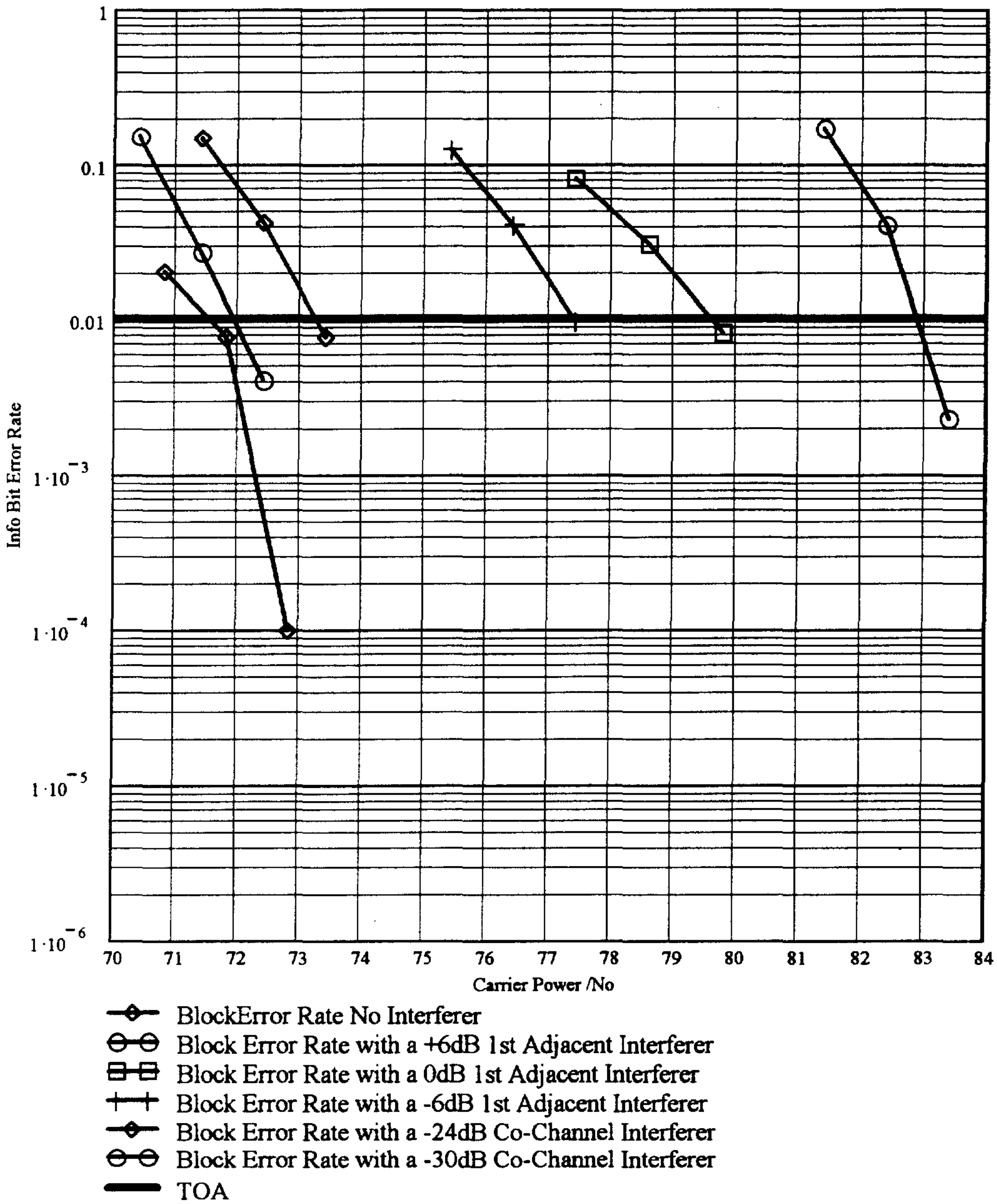


Figure K-7 Performance results for the AM hybrid system in the presence of both AWGN and interference.

5. Summary and Conclusions

USADR has performed laboratory tests to characterize the performance of the hybrid IBOC signal in the presence of Gaussian noise and the results are depicted in Figure K-7.

These tests demonstrate that the IBOC digital signal is tolerant of high levels of adjacent channel interference. Furthermore the co-channel performance exceeds the FCC's protected contour by greater than 7 dB. These tests verify the real-time performance of the USADR hardware as predicted by the computer simulations. Testing has provided substantial evidence that the USADR AM hybrid IBOC system provides coverage near or in excess of FCC's protection criteria.

Appendix L

Appendix L

AM Hybrid IBOC DAB Field Test Results

1. Overview

The USADR AM IBOC DAB system has been carefully designed to provide superior digital audio performance while minimizing the impact to existing analog signals. In the initial phase of development, the system was modeled and simulated to verify that the resulting design would exhibit acceptable performance in an environment comprised of both analog and IBOC signals. As the development has progressed, the computer models have been replaced by hardware and software implementations of AM IBOC DAB exciters and receivers. These exciters and receivers allow for verification of system performance in the field.

The goals of the USADR AM field testing program are four fold: (1) Demonstrate significant improvements over current analog audio quality; (2) Demonstrate robustness of the digital signal in the harsh AM environment (e.g., robustness to interferers as well as channel impairments); (3) Demonstrate coverage areas large enough such that significant numbers of listeners currently receiving analog broadcasts will be able to receive digital broadcasts; and (4) show that the hybrid IBOC DAB signal is compatible with existing analog signals.

This appendix describes the procedures being used for AM field testing, and provides preliminary results. These tests are important because they verify the performance of a physical implementation of the design under real-world conditions.

2. Definitions and Assumptions

2.1. DAB Signal

The desired hybrid IBOC signal is comprised of an analog AM host and a DAB signal. Both the analog AM and DAB signals are generated using a USADR AM IBOC DAB exciter for further amplification by existing analog transmitters. Figure L-1 depicts a spectral representation of the AM hybrid IBOC signal.

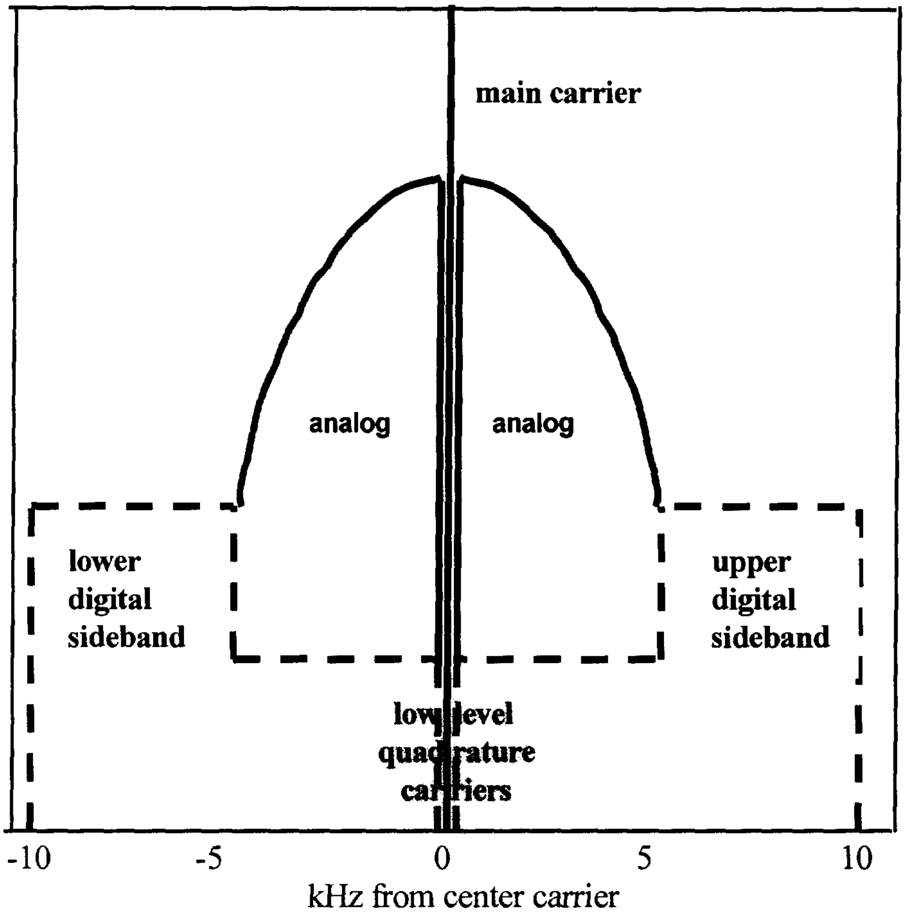


Figure L-1 - AM Hybrid IBOC Spectrum

2.2. Digital Coverage

The USADR IBOC DAB system employs a time-diversity blend function which allows graceful degradation of the digital signal as the receiver nears the edge of a station's coverage. When the primary digital signal is sufficiently corrupted, the receiver blends to analog audio.[1]

The receiver uses the block error rate [2] metric to determine the appropriate time to commence a blend to analog. As the received signal degrades, blends will occur with

[1] Refer to Appendix I for a discussion of USADR's time-diversity blend function.

[2] Blocks are simply large groups of information bits at the input to the audio decoder. Each block has an assigned cyclic redundancy check (CRC). If the block's CRC is incorrect, the block is deemed in error.

increasing frequency. The edge of digital coverage is defined as the point at which the receiver no longer blends back to digital.

3. Test Setup

3.1. Transmitter Test Sites

WD2XAM, an experimental, 10 kW station operating at a frequency of 1660 kHz, is currently being used for initial AM field testing. The transmit antenna is located at Xetron Corporation in Cincinnati, Ohio, at a longitude of 84° 28' 40" W and a latitude of 39° 18' 16" N. Xetron is performing tests to obtain coverage results along eight radials. The radials were chosen to correspond to approximately 45 degree increments in azimuth around the transmitter. The radials covered a wide variety of reception environments including urban, suburban, rural, heavy industrial/business, light industrial/business, and residential. A wide variety of road types were encountered, including divided highway, two-lane non-divided highway, high traffic non-highway, and light traffic non-highway.

3.2. Station Configuration

Figure L-2 shows the equipment configuration that is being used to generate the transmitted signal. The source material to be played was recorded on a CD. The Denon DN-C680 CD player sampling frequency was synchronized to the oscillator in the USADR exciter to prevent data underflow or overflow errors for the audio encoder. Synchronization was accomplished by inputting a 44.1 kHz signal from the exciter to the CD player external synchronization input. The CD player output was input to the an Orban Optimod 9200 audio processor. The processed source material was input to the USADR exciter via an AES/EBU connection. The audio signal was encoded by the exciter, and the hybrid DAB signal, containing the analog and digital components, was generated.

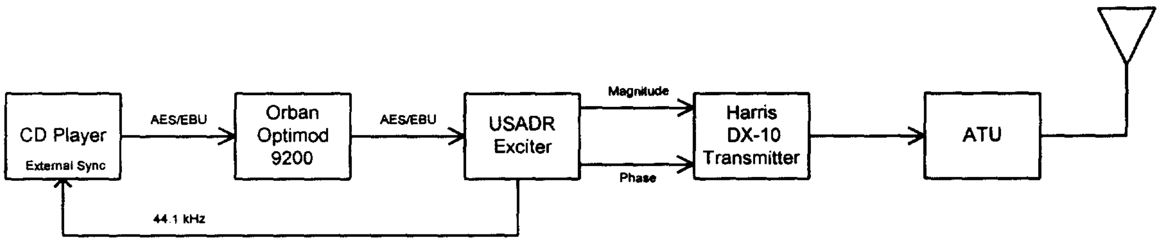


Figure L-2 - Diagram of Xetron AM Transmitter Setup

The USADR exciter produced magnitude and phase components that are input to a DX-10 transmitter supplied by Harris Corporation. The phase signal was input to the external oscillator input on the Harris DX-10. The magnitude signal produced by the exciter contains the DC bias needed for AM broadcasting. Although the Harris DX-10 transmitter usually provides the DC bias, the modulation index and the level of the digital signal relative to the analog signal could be conveniently and precisely controlled by having the exciter provide it.

A modulation index was adjusted to be consistent with normal operating levels (-99, +125%). This level refers to the modulation of the analog signal only. The modulation levels were checked by observing the Harris DX-10 transmitter modulation-monitor sample signal, and the signal received at the test van, with an oscilloscope.

The signal from the Harris DX-10 transmitter was sent to the antenna tuning unit (ATU) using a 580 foot section of Andrew LDF6-50 Heliax coaxial cable. The output from the antenna tuning unit was input to the transmit antenna. Central Tower Corporation supplied the transmit antenna, which is 150 feet high and base-fed. The antenna has a ground system consisting of 120, 150' buried radials.

3.3. Van Configuration

Mobile test platforms were created to collect data while performing field tests. Test vans were modified to support the equipment and interfaces shown in Figure L-3. Test data is acquired and stored using USADR's Field Test PC application. Table L-1 describes the manufacturer and model number of the test equipment in the van.

The signal was received through a 31" whip antenna mounted on top of the test van. The antenna was connected to the receiver using a 4.5 foot piece of RG62 coaxial cable, which has a characteristic impedance of 93 ohms. This particular antenna and cable were used because they are typical of equipment on many automobiles.

The Field Test PC provides a graphical user interface ("GUI"), similar to that shown in Figure L-4. This application controls and collects data from three sources:

- GPS receiver
- Spectrum analyzer
- DAB receiver

3.3.1. GPS Receiver Data and Processing

The following data is collected by the GPS receiver over an RS-232 interface[3]:

- GPS time
- GPS position (latitude and longitude)

During setup, the operator enters the position of the transmitter. Current latitude and longitude are then taken directly from the GPS receiver and displayed. The application uses this information to compute and display the current distance from the transmitter.

---

[3] RS-232 is an industry standard serial communications link used by PCs and test equipment.

3.3.2. Spectral Data and Processing

The following data is collected by the Spectrum Analyzer over a GPIB interface:[4]

- Lower first-adjacent signal level
- Upper first-adjacent signal level
- Lower second-adjacent signal level
- Upper second-adjacent signal level
- Desired signal level

This data is then displayed directly by the Field Test PC application.

3.3.3. DAB Receiver Data and Processing

The following data is collected from the DAB receiver over an RS-232 interface:

- Desired signal strength
- DAB receiver audio mode (digital or analog)
- Cumulative blend counter, which increments whenever the receiver changes its blend status.

3.3.4. PC Application

This application displays new data from each device every eight seconds. All data shown on the display is also stored to a file. The data stored in this file is then re-formatted to generate a strip-chart recording, which plots the variation of select parameters with time over the length of the test.

3.3.5. Video Processing and Storage

Video cameras are mounted on the front and back of each test van. The output from each camera, along with the video display from the spectrum analyzer, are multiplexed into one image by a quad-screen controller, and recorded on videotape. The operator keeps logs to coordinate the stored images with the data collected by the Field Test PC application.

3.3.6. Audio Processing and Storage

During Digital Coverage testing, the Akai DR8 digital audio recorder is capable of simultaneously recording audio from the Delco and USADR IBOC receivers. For First-Adjacent and Host Compatibility Testing, the digital audio recorder is capable of simultaneously recording audio from all analog test receivers and the USADR IBOC receiver. All audio and video equipment is controlled manually.

4 GPIB is a communications protocol and interface used by PCs to communicate with test equipment.

Type	Manufacturer	Model
Spectrum Analyzer	Hewlett Packard	HP-8591
Video Multiplexer	Capture	CPT-MQ4
VCR	AVE	RT195
Video Camera(s)	Marshall	V1212BNC
GPS Receiver	Garmin	GPS II
Digital Recorder	Akai	DR8 Hard Disk
Car Stereo	Delco	16195167

Table L-1 – Test Equipment Manufacturer and Model numbers

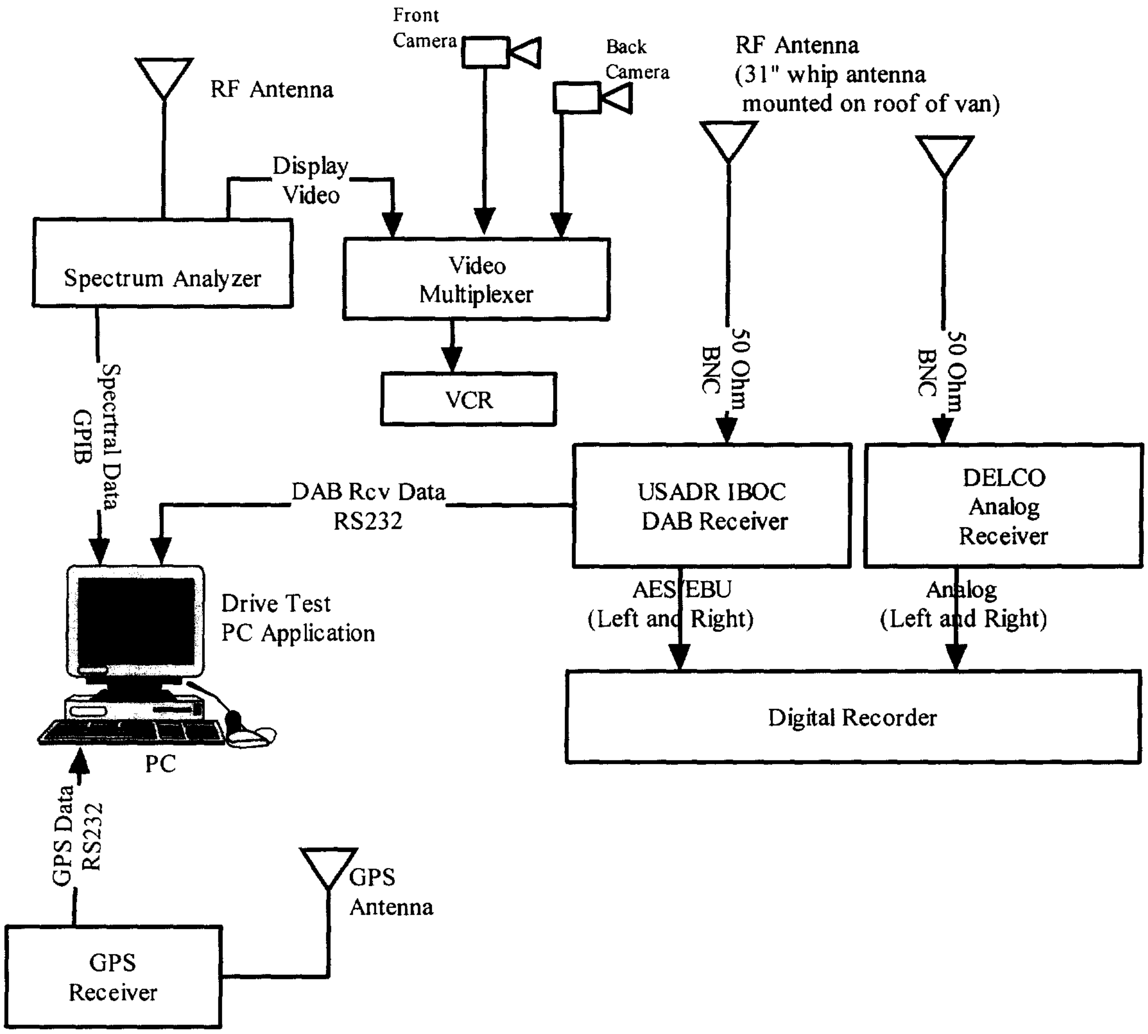


Figure L-3 - Test Van Equipment Setup

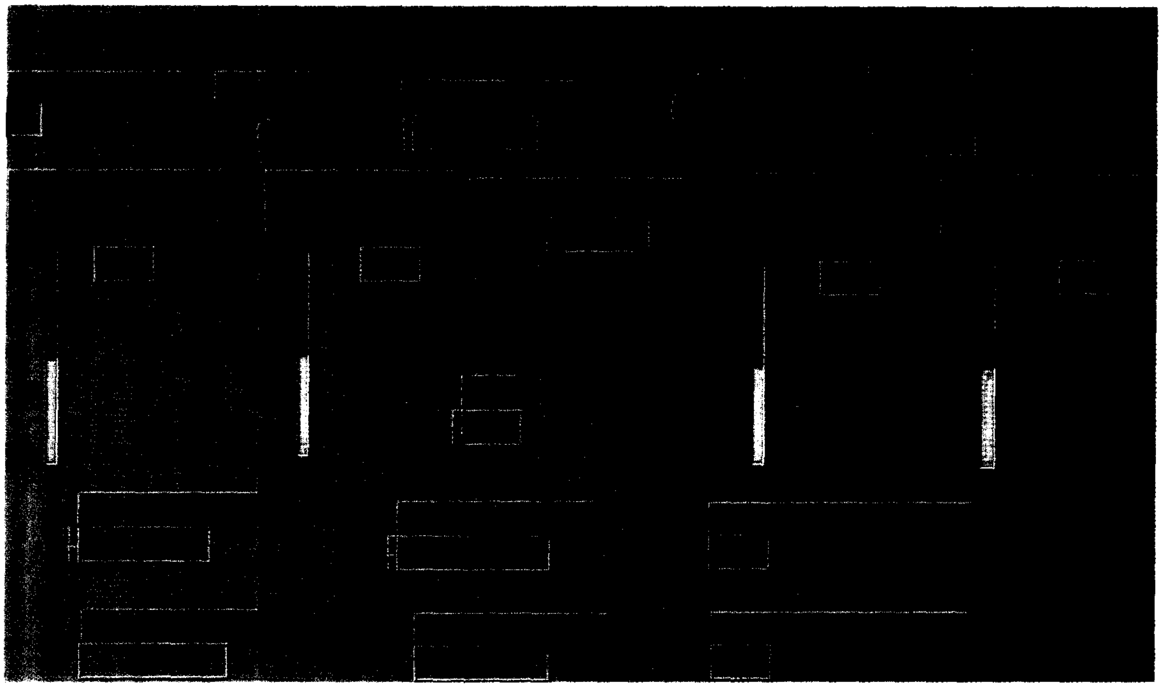


Figure L-4 - USADR Field Test PC Application Display (GUI)

4. Digital Coverage Test

4.1. Overview

This test measured the digital coverage of the WD2XAM hybrid IBOC signal. During the test the following information was stored:

- Data from the Field Test PC application
- Video from the spectrum analyzer
- Video from the front and back cameras
- Audio from the Delco and USADR IBOC receivers

4.2. Route Selection

The following steps were followed to create the routes traveled by the test vans:

- Radials were plotted for the selected azimuth lines from the transmitter site.
- The shortest driving routes were selected to approximate the desired radials.[5]
- Driving instructions from commercial mapping software were obtained for each route.
- Efforts were made to route the van through areas of varying terrain, with urban and suburban population densities.

5 Preferences were given to major roads along each route.

4.3. Test Procedure

a) At the starting location, tune the PC, the IBOC receiver, and the Delco receiver to the desired operating frequency. Enter the GPS coordinates of the transmitter site into the PC. Load the recording media into the Digital Audio Recorder, set the analog audio levels, and label the audio cut. Place a tape into the VCR and setup to record.

b) All notes, tapes, and data should have the same time reference, which is derived from the GPS. Be sure all clocks are synchronized.

c) Simultaneously begin recording on the VCR, Digital Audio Recorder, and PC.

d) Follow driving instructions for the selected radial. Proceed to the end of the planned route, or to a point several miles beyond the edge of digital coverage.

e) Close all files, and remove and mark all tapes.

f) Repeat steps a) through e) for all radials.

4.4. Preliminary Test Results

Figure L-5 shows preliminary results of the coverage tests performed thus far. This map, using data recorded by the Field Test PC application, color codes the audio mode of the IBOC receiver along each field test radial. The colors signify three main regions of IBOC coverage:

- Region 1 (Green) indicates the portion of the radial where digital audio is uninterrupted;

- Region 2 (yellow) indicates the portion of the radial where the audio is blending between analog and digital;

- Region 3 (red) indicates the portion of the radial where digital audio is no longer available, and the receiver has blended to analog.

IBOC field performance may be further illustrated by analyzing the full suite of test data recorded along each of the radials. For illustration purposes, USADR has selected one of these radials for analysis in this report: the radial that runs northeast along Route 71 away from Cincinnati.

The test data, presented via strip-chart recording comprised of data logged by the Field Test PC application, is shown in Figure L-6. The strip chart displays the variation of select parameters with time over the entire length of the radial. The following parameters are included on the strip chart:

- Desired signal strength, in mV/m (red)
- Upper (blue) and lower (yellow) first-adjacent signal strength, in mV/m
- Upper (black) and lower (magenta) second-adjacent signal strength, in mV/m
- Distance from the transmitter, in km (orange)

- Receiver audio mode, digital or analog (green)

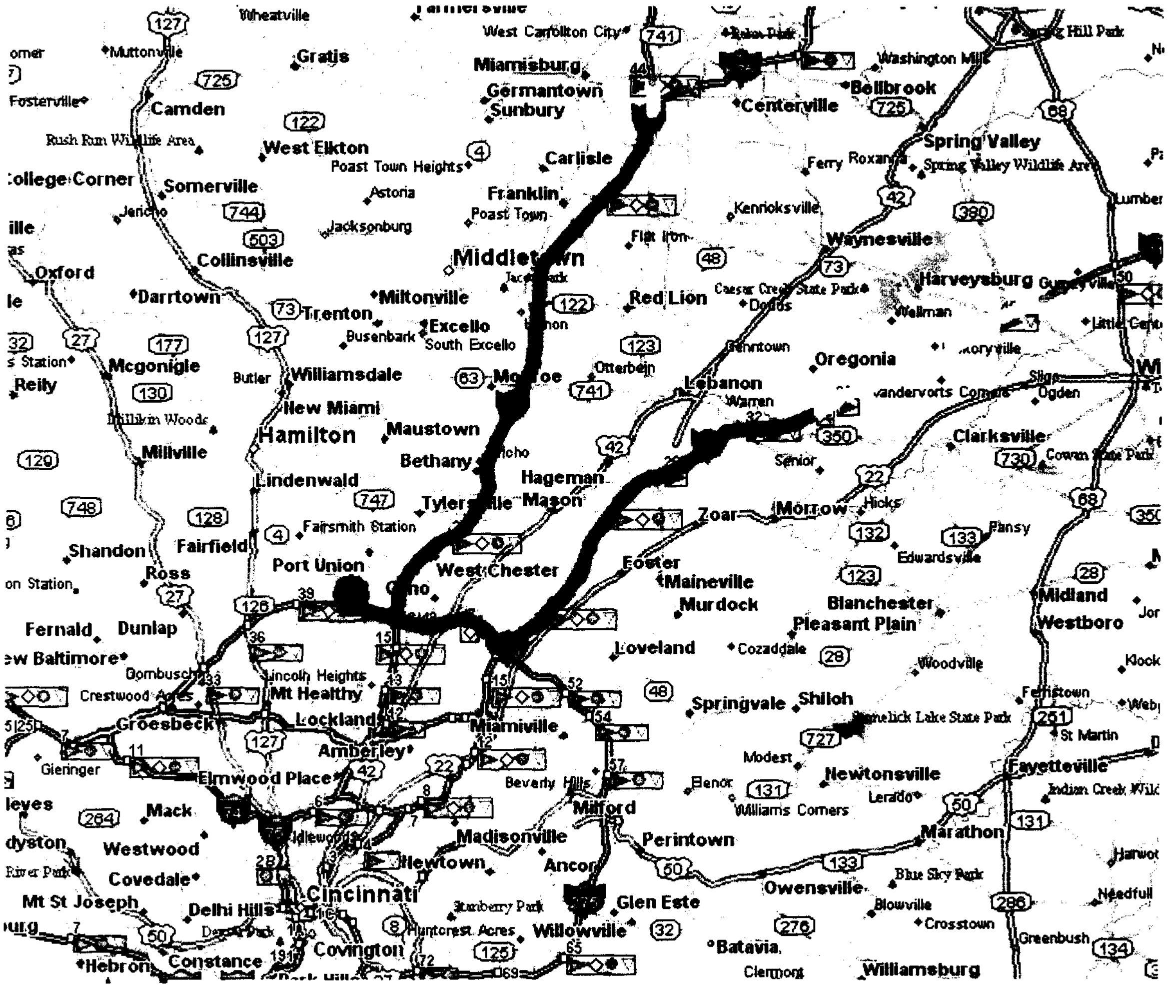


Figure L-5 WD2XAM AM IBOC Coverage Map
(Scale: 1 inch = 10 miles)